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Stochastic resonance in a time polo-delayed asymmetry bistable system driven by multiplicative white noise and additive color noise

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ABSTRACT

Stochastic resonance (SR) in a time polo-delayed asymmetry bistable system driven by multiplicative white noise and additive color noise is investigated in this paper. First, the effective potential function is deduced based on probability density approach theory, small delay approximation theory and colored noise approximation theory. Second, the mean first-passage time (MFPT) which plays an important role in investigating on particles escape rate is derived and we find that the effect of additive color noise is more observable than that of multiplicative white noise on MFPT. Finally, influences of different parameters on SR are studied by signal-to-noise ratio (SNR). The analytic expression of SNR is derived and three-dimensional graphs of SNR with different parameters are obtained. We conclude that time delay τ and time delay strength e can suppress SR and that asymmetric item r has a non-monotone effect on SR. The results also suggest that adjusting the additive noise intensity Q is more sensitive than that of the multiplicative noise intensity D in controlling SNR.

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1. Introduction

Stochastic resonance (SR) is a significant phenomenon that can enhance the output signal-to-noise ratio (SNR) in nonlinear dynamical systems. This phenomenon was originally proposed by Benzi and Nicolis in the 1980s for explaining quaternary glaciers [1–3]. Since then, SR has extensively been studied and applied in various fields [4–11]. McNamara et al. [12,13] observed SR phenomena via a bidirectional ring laser and studied the expression of the SNR using the adiabatic approximation theory. Dykman et al. [14] innovatively introduced a neoteric method, which is the linear response theory for investigating SR. Bag et al. [15] discussed the mean lifetime for the escape of a Brownian particle through an unstable limit cycle driven by multiplicative colored Gaussian and additive Gaussian white noises. Zhou et al. [16] studied SR in an asymmetric bistable system driven by correlated noise, and found that the effects of potential asymmetry and the strength of the coupling between the noises had opposing effects on the SNR. Wang et al. [17,18] introduced a time delay into SR and concluded that such delays could produce different effects on SR by changing the parameter values. Shi et al. [19–22] studied the characteristic of SR and its application in weak signal detection. He et al. [23,24] investigated SR in an over-damped fractional oscillator subject to multiplicative dichotomous noise. Lu et al. [25,26] proposed a non-stationary weak signal detection strategy based on a time-delayed feedback stochastic resonance model, and proved that this method was suitable for the detection of signals with strong nonlinear and non-stationary properties. Guo et al. [27] studied SR phenomena in a piecewise nonlinear model driven by a periodic signal and correlated noises, and discussed the effects of non-Gaussian noise and Gaussian noise on SR.

Since the beginning of the 21st century, researchers have begun to attach importance to the study of time delay in nonlinear dynamical systems. Time delay exists in physics systems, nervous systems, and energy systems and so on. Therefore, time delayed systems can be regarded as simplified, but very useful, descriptions of systems that involve a reaction chain or a transport process. Based on the concept of delay Fokker-Planck equations, Frank [28,29] investigated nonlinear stochastic systems with time delay and derived the small delay approximation theory. Du et al. discussed the effects of global-time delay and polo-time delay separately in bistable systems [30]. Guo et al. discussed SR in a tumor-immune system subject to bounded noises and time delay [31]. Han et al. studied impact of time delays on stochastic resonance in an ecological system describing vegetation, [32]. Wang et al. discussed impact of delays and rewired on the dynamics of small-world neuronal networks with two types of coupling [33]. Guo et al. studied SR in a time-delayed bistable system and a mono-stable system subject to multiplicative and additive noise [34]. An increasing

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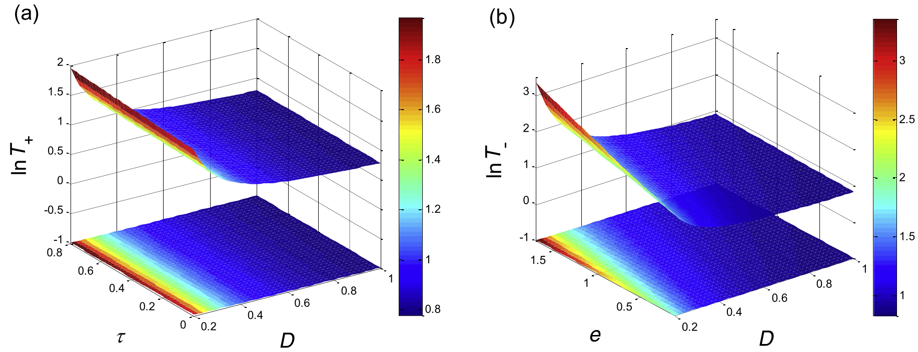

Fig. 1. The MFPT with fixed $H = 0.1$, $Q = 0.3$, $r = 0.3$, $\tau_1 = 0.3$ for various D, τ and e: (a) $\mathrm{MFPT}_{x_{s_1} \to x_{s_2}}$ with fixed e=0.3 and various D and τ; (b) $\mathrm{MFPT}_{x_{s_2} \to x_{s_1}}$ with fixed τ=0.1 and various D and e.

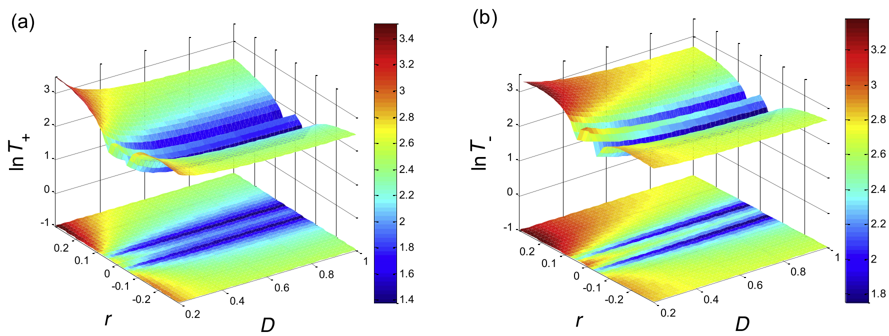

Fig. 2. The MFPT with fixed $H = 0.1$, $Q = 0.3$, $e = 0.3$, $\tau = 0.1$, $\tau_1 = 0.3$ for various D and r. (a) $\mathrm{MFPT}_{x_{s_1} \to x_{s_2}}$ with various D and r; (b) $\mathrm{MFPT}_{x_{s_2} \to x_{s_1}}$ with various D and r.

number of studies on nonlinear stochastic systems with time delay have appeared in recent years [35–41]. However, to the best of our knowledge, no study has investigated time polo-delayed asymmetric bistable systems driven by multiplicative white noise and additive color noise.

This paper studies SR phenomena in a time polo-delayed asymmetric bistable system driven by multiplicative white noise and additive color noise. In Section 2, we deduce the Langevin equation and the general potential function of this system. Section 3 describes the influence of various parameters on the mean first-passage time (MFPT). The effects of the parameters on the SR phenomena are investigated in Section 4. Finally, the conclusions are stated in Section 5.

2. Time polo-delayed asymmetric bistable system

The traditional Langevin equation is given by

$$\frac{dx}{dt} = ax - bx^3 + A\cos(\omega t) + \xi(t) \tag{1}$$

Du L. C. and Mei D. C. investigated a bistable system with global delay and two noises [42]. The Langevin equation of the system is written as below:

$$\frac{dx}{dt} = ax(t-\tau) - bx(t-\tau)^3 + A\cos(\omega t) + x(t-\tau)\xi(t) + \eta(t) \tag{2}$$

Guo Y. F et al studied stochastic resonance in a time-delayed asymmetric bistable system with mixed periodic signal [43]. They describe the relevant Langevin equation as follow:

$$\begin{aligned}\frac{dx}{dt} &= ax(t-\tau) - bx(t-\tau)^3 + f_1\cos(\omega_1 t) \\ &\quad + f_2\cos(\omega_2 t) + r + x\xi(t) + \eta(t)\end{aligned} \tag{3}$$

Through these three equations we can see that both in Eq. (2) and Eq. (3) the x and x^3 of the system contain the time delay τ, which we call the system with global delay. In this article we consider the time delay τ exists only in x but not exists in x^3, which we call a time polo-delayed system. So the Langevin equation of a time polo-delayed asymmetric bistable system driven by a periodic signal, uncorrelated multiplicative noise $\xi(t)$, and additive noise $\eta(t)$, can be described by the following [44]:

$$\frac{dx}{dt} = ax - bx^3 + r + ex(t-\tau) + A\cos(\omega t) + x\xi(t) + \eta(t) \tag{4}$$

where τ is the time delay, e is the time delay strength, r is the asymmetric item, and$A$ and ω denote the amplitude and frequency of the periodic signal, respectively. $\xi(t)$ and $\eta(t)$ represent white noise and colored noise respectively, and each noise term is characterized by its respective mean and variance

$$\begin{aligned}&\langle\xi(t)\rangle = \langle\eta(t)\rangle = 0 \\ &\langle\xi(t)\xi(t')\rangle = 2D\delta(t-t') \\ &\langle\eta(t)\eta(t')\rangle = \frac{Q}{\tau_1}\exp\left(-\frac{|t-t'|}{\tau_1}\right) \\ &\langle\xi(t')\eta(t')\rangle = \langle\xi(t')\eta(t)\rangle = 0\end{aligned} \tag{5}$$

where D and Q are the intensities of the multiplicative and additive noise, respectively, and τ_1 denotes the correlation time of $\eta(t)$.

The nonlinear dynamics described by Eq. (4) correspond to a non-Markov stochastic process. Using the probability density approach and small delay approximation, we transform the non-Markov process into a Markov process. Without the loss of generality, we set $a = 1$, $b = 1$. Thus, Eq. (4) can be replaced by the following effective Langevin equation

$$\begin{aligned}\frac{dx}{dt} &= (1 + e + e\tau + e^2\tau)x - (1 + e\tau)x^3 + (1 + e\tau)(r + A\cos(\omega t)) \\ &\quad + x\langle\xi(t)\rangle + \langle\eta(t)\rangle\end{aligned} \tag{6}$$

Using the unified colored noise approximation, we obtain the time polo-delayed Fokker-Planck equation, written as

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